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LOW PRESSURE, HIGH VOLTAGE DISCHARGES FOR THE PRODUCTION OF ENE--ETC(U)
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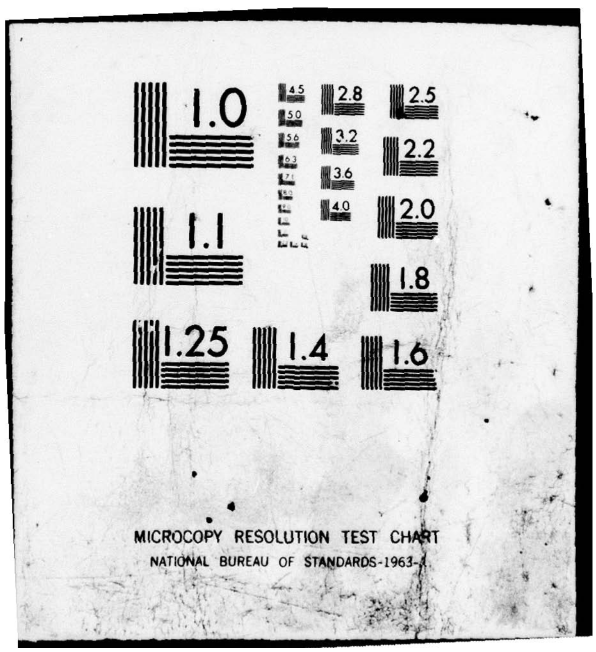
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19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The fundamental theories of gas discharges offer widely varying predictions for the relative power input to the negative glow. Calorimetric measurements have been made in a planar helium discharge of the power input to the negative glow relative to the total input power. These measurements show that the limiting efficiency of devices working in this region (e.g., hollow cathode lasers) is approximately 30-40%. To aid in the interpretation of the experimental results a simplified theoretical model was derived.

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LOW PRESSURE, HIGH VOLTAGE DISCHARGES

FOR THE PRODUCTION OF ENERGETIC ELECTRON BEAMS

Final Report

for

Grant DAHC-04-75-G0132

Project No. P-12528-P

20 May 1975 to 20 May 1979

Submitted by

J. T. Verdeyen, Professor

Gaseous Electronics Laboratory
Department of Electrical Engineering
University of Illinois at Urbana-Champaign
Urbana, Illinois 61801

SUMMARY

Herewith is enclosed a paper which represents the results of the work carried out under this contract from June 1978 to May 1979.

The impetus to these experiments lies in the discordant way in which basic gas discharge theory deals with the energetics of the cathode fall and negative glow; the cathode fall voltage times the input current represents a power input, presumably to portions of the discharge other than the positive column. Depending upon the particular theory chosen, either all or none of this input goes to the negative glow. To find out what fraction of this "input power" is delivered to the negative glow and which is therefore available for use in, e.g., hollow cathode lasers, we undertook a calorimetric measurement of the power flux entering the negative glow from the cathode fall. A thermistor was mounted in the tip of a glass probe and calibrated to measure incident power flux due to beam electrons. A variety of refinements were developed to circumvent problems with undesired thermal inputs to the probe, and the most important of these are described in the accompanying paper. Helium was chosen as the working medium, and in the pressure range studied (.24 to .8 torr.) the power fraction input to the negative glow was found to be about 0.3 to 0.4.

To aid in better understanding our data, a simplified theoretical model was developed which, although it makes some drastic assumptions, does appear to give reasonable results, in comparison both with other theoretical models and the results of our own experiments. A description of this model is outlined in the paper enclosed. The unique feature of this model is that it does not rely upon sophisticated computer analysis; rather, its results are in rather elementary functions. Nonetheless, it has provided another valuable insight into the cathode fall region.

List of Publications

Submitted for publication - see Appendix A.

List of Participating Scientific Personnel

B. E. Cherrington

J. T. Verdeyen

S. T. Griffin

M. H. Simmons

S. Hutchinson

Advanced Degrees Earned

S. Hutchinson - Master of Science

S. Griffin - Master of Science

M. Simmons - Master of Science

APPENDIX A

ENERGETICS OF THE NEGATIVE GLOW*

ABSTRACT

The fundamental theories of gas discharges offer widely varying predictions for the relative power input to the negative glow. Calorimetric measurements have been made in a planar helium discharge of the power input to the negative glow relative to the total input power. These measurements show that the limiting efficiency of devices working in this region (e.g., hollow cathode lasers) is approximately 30-40%. To aid in the interpretation of the experimental results a simplified theoretical model was derived.

*This work supported by Army Research Organization, Durham, NC.

I. INTRODUCTION

This paper describes the results of direct measurements of power flux at the cathode fall-negative glow boundary by means of a calorimetric probe. These measurements can serve as an indication of the fractional power input to the negative glow.

In a typical planar discharge as shown in Fig. 1, the input current density times the cathode fall voltage represents the power flux to discharge regions other than the positive column. Some of this power is deposited within the negative glow; part may be used in the cathode fall region for electron multiplication; and ions diffusing toward the cathode from the negative glow gain energy from the field in the cathode fall and deposit it at the cathode. Our interest centers on the question of what fraction of this power enters the negative glow in the form of energetic (beam) electrons. It is this fraction which is available for ionization and excitation within the negative glow, which, in turn, is essential to the operation of hollow cathode devices, in particular hollow cathode lasers. Thus, the ultimate efficiency of any hollow cathode laser is limited by this fraction.

This region has been explored for some time using electrostatic probes. However, aside from the obvious modifications of the cathode fall fields by the presence of a conducting probe, it has been pointed out in measurements by Popa, et al[1] that secondary electron emission can modify Langmuir probe data, and that this effect is directly related to the probe orientation. Pringle and Farvis[2] employed an improved screened probe to measure electron energy distributions, but such a device might still create unacceptable perturbations in the behavior of this region. In addition, analysis of the near-cathode region can lead

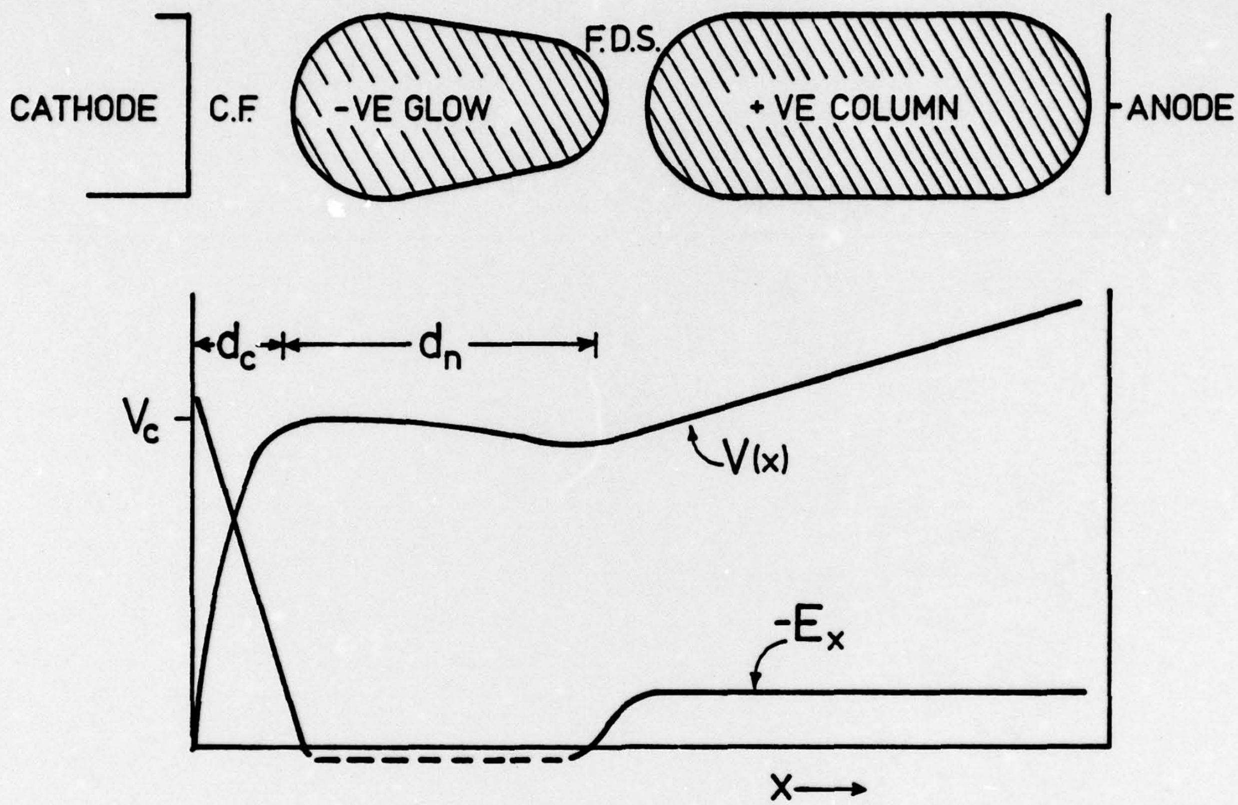

Fig. 1. Typical Planar Discharge.

to a better understanding of the processes leading to cathode heating, which, in turn, can cause a "cold" cathode to become a thermionic emitter with accompanying glow-to-arc transition so necessary in the operation of many lamps and so disastrous in high pressure positive column lasers.

The analysis of the cathode fall has proceeded with a variety of attempts to rationally describe this region. For example, on a basic level, the electron flux growth in the cathode fall may be described by the widely-used Townsend equation:

$$\frac{d\Gamma}{dx} = - \alpha \left(\frac{E(x)}{p}\right) \Gamma .$$

Strict application of the coefficient α (which is a function of E/p) requires that the electrons be in equilibrium with the field. Since $E(x)$ is low at the cathode fall-negative glow boundary one should expect that ionization and excitation must also be low there in order to be consistent with this formulation. Obviously, ionization and excitation are not low there, and the weak link is that electrons are not in equilibrium with the field.[1-3] Nevertheless, calculations based upon the above equation have had a degree of success. For instance, Ward[4] employed the ionization coefficient α along with the space charge distortion of the field in the cathode fall to describe the fundamental overall characteristics of this region with impressive results. Likewise, Itoh and Musha[5] have used Monte Carlo techniques to determine mean values of α/p_o in helium based upon the mean behavior of a single electron.

At the other extreme, one may view the length of the negative glow, as does Cobine[6] or von Engel,[7] as representative of the range of electrons which have attained the full cathode potential in energy. If an appreciable number of electrons have this energy, the fractional power entering the negative glow may be close to unity. Measurements of the energy spectrum of electrons entering the negative glow in a helium discharge by Pringle and Farvis[2] suggest that such a simple theory will not work, and that the processes in the negative glow are governed by perhaps three groups of electrons having widely varying energy spectra.

Electron behavior in the cathode fall has also been predicted more extensively through the use of statistical, or Monte Carlo, techniques. By studying the statistical histories of electrons in the cathode fall on the basis of a chosen model, it is possible to describe the features of this region in terms of the cause and effect relationships. Thomas and Thomas[8] employed Monte Carlo techniques to study the avalanche growth of electron current in gas discharges to improve previous theoretical predictions of the primary ionization coefficient and excitation cross section. Tran, et al.[9] have used a one dimensional model for helium which confirms the three temperature model of Pringle and Farvis and which may also help explain the cathode region of high-pressure corona discharges.[2] Finally, one may consider the theroetical analysis presented below as an analytic approximation to the Monte Carlo calculations to aid in interpreting experimental results.

II. THEORETICAL ANALYSIS

Any model of the cathode fall must account for electron current growth while satisfying the principles of Boltzmann's equation. A number of theories concerning electron current growth within the cathode fall have been postulated, each with its own merits and weaknesses (as discussed previously).[3,6,7] Presented below is a relatively simple theory which avoids some of the pitfalls mentioned earlier but which arrives at a reasonable approximation for the electron energy distribution without a solution of Boltzmann's equation. Such an analysis does not pretend to allow precise calculation of the electron energy distribution in the cathode fall, but does give reasonable estimates to aid in the evaluation of experimental results. Various simplifying assumptions have been made which permit an analytic solution not requiring detailed computer analysis.

In order to simplify the bookkeeping in our analysis, we assume an ionization event results in two slow electrons via:

$$e^- \text{ (fast)} + M \rightarrow M^+ + e^- \text{ (slow)} + e^- \text{ (slow)}. \qquad (1)$$

Although this assumption violates conservation of energy, it greatly simplifies the mathematics. While the flux of the high energy electrons is significant, their number is small, and thus the violation is not so serious.

The cathode fall region is divided into n segments, each Δx long, and labelled by the subscript j. Thus the flux originating in each segment attenuates due to collisions as it is accelerated toward the negative glow.

$$\frac{d\Gamma_j(x)}{dx} = - N\sigma_i(\varepsilon)\,\Gamma_j \quad , \quad x > x_j \qquad (2)$$

Here N is the neutral atom density and $\sigma_i(\varepsilon)$ is the ionization cross-section.

The flux originating in Δx at x_j is the result of the flux originating at all prior segments at points $x < x_j$, according to:

$$\Gamma_j (x_j) = 2 \sum_{k=0}^{j-1} \Gamma_k (x_{j-1}) - \Gamma_k (x_j) \qquad (3)$$

where the difference in Γ's is based upon Eq. (2). The factor of 2 comes from the fact that the ionization event produces two electrons. At this point we make a final assumption: we ignore the energy dependence of the ionization and let $\sigma_i(\varepsilon) = \sigma_i$, even down to zero energy. While this assumption is indefensible, it allows all subsequent manipulations to be handled by elementary functions. Both this and the prior assumption have been avoided by computer analysis with little difference in results.

Now Eq. (2) can be integrated, substituted into Eq. (3) and simplified:

$$\Gamma_j (x_j) = 2(1-e^{-\rho\Delta x}) \sum_{k=0}^{j-1} \Gamma_k (x_j)\, e^{-\rho(x_{j-1}-x_k)} \qquad (4)$$

or

$$\Gamma_j (x_j) \doteq 2(1-e^{-\rho\Delta x}) (2-e^{-\rho\Delta x})^{j-1} \qquad (5)$$

where $\rho = N\,\sigma_i$.

Equation (5) can now be used in Eq. (4) to obtain the spatial variation of the flux originating in any segment within the cathode fall.

$$\Gamma_j (x) = 2\Gamma_o(1-e^{-\rho\Delta x}) (2-e^{-\rho\Delta x})^{j-1}\, e^{-\rho(x-x_j)} \qquad (6)$$

Our main interest is in the flux entering the negative glow at x = d. If d is the length of the cathode fall ($\Delta x = \frac{d}{n}$), then we may use Eq. (6) to find the flux entering the negative glow

$$\Gamma_e(d) = \sum_{j=1}^{n} \Gamma_j(d) + \Gamma_o\, e^{-\rho d}$$

or

$$\Gamma_e(d) = \Gamma_o\, e^{-\rho d}(2e^{\rho d/n}-1)^n \tag{7}$$

and upon taking the limit as $n \to \infty$, we have

$$\Gamma_e(d) = \Gamma_o\, e^{\rho d} \tag{8}$$

Thus, based upon a logic completely different than that normally chosen, one arrives at a solution of the form

$$\Gamma(d) = \Gamma_o\, e^{\alpha d}$$

which is the familiar electron flux growth equation in wide practical use.

The above result may be used to give an estimate of the fractional power delivered by electrons to the negative glow, (R). If $v_j(x)$ is the velocity of the j^{th} flux

$$\Phi_j(x) = v_j(x)\, \Gamma_j(x) = \sqrt{\frac{2e}{m}\,[V(x) - V(x_m)]}\; \Gamma_j(x). \tag{9}$$

Within the cathode fall, let

$$\vec{E} = \frac{-2V_c}{d}\left(1 - \frac{x}{d}\right)\hat{x}, \text{ so that}$$

$$V(x) = \frac{2V_c}{d}\left(x - \frac{x^2}{2d}\right) \qquad (10a)$$

and

$$V(x_j) = \frac{2V_c}{d}\left(x_j - \frac{x_j^2}{2d}\right) \qquad (10b)$$

With Eqs. (10a and 10b), Eq. (9) becomes:

$$\Phi_j = \sqrt{\frac{2e\,V_c}{m}}\left(\frac{n^2 - j^2}{n^2}\right)^{1/2} \Gamma_j .$$

The total power flux entering the negative glow is then the sum of Φ_j over $0 \leq x \leq d$, $1 \leq j \leq n$. Thus the fractional power entering the negative glow is

$$R = \frac{\Phi}{\sqrt{\frac{2eV_c}{m}}\;\Gamma_o\, e^{\rho d}} \qquad (11a)$$

or

$$R = e^{-2\rho d}\left\{1 + \frac{2}{n}\left(e^{-\rho d}/n-1\right)\sum_{k=0}^{n-1}\left(2e^{\rho d}/n-1\right)^k \left(n^2 - (k+1)^2\right)^{1/2}\right\} \qquad (11b)$$

where $k = j-1$.

Values of R from this approximate model are plotted in Fig. 2 for $n = 1000$. Although based on crude assumptions, this model does indicate that the fractional power entering the negative glow lies between the limits implied by basic theory.

This model can also yield an approximation of the energy distribution of electrons entering the negative glow. For the number of electrons at the cathode fall-negative glow boundary (x=d) from the plane at $x = x_j$, one has

$$N_j(d) = \frac{\Gamma_j(d)}{v(x_j)} = \frac{\Gamma_j\ (d)}{\sqrt{\frac{2e}{m}\ (V(x) - V(x_j) + \frac{V_c}{n})}} \tag{12}$$

The increment $\frac{V_c}{n}$ is added here to eliminate division by zero at any point. The total number entering the negative glow is then

$$N_T = \frac{\Gamma_o}{\sqrt{\frac{2e\ V_c}{m}}} \{1 + 2(e^{\rho d}/n-1) \quad \sum_{j=1}^{n} \frac{(2e^{\rho d/n}-1)^{j-1}}{\sqrt{1 + \frac{1}{n} - j^2/n^2}} \tag{13}$$

thus,

$f_j = \frac{N_j(d)}{N_T}$. For n = 100 distributions are plotted in Fig. 3 for ρd = 0.1, 1 and 10. It can be seen from these curves that increasing $\rho d = N\ \sigma_i d$ decreases the number of high energy electrons at the cathode fall-negative glow boundary. At large values of ρd the distribution contains predominantly low energy electrons, those which have been produced close to the cathode fall. At lower ρd values, the distribution function appears also to include a large group of intermediate energy electrons which have undergone collisions within the cathode fall where the electric field is still strong enough to accelerate them. The results of this simplified model therefore do follow somewhat the features of other theoretical and experimental models which have indicated the existence of three groups of electrons within the cathode fall.[2,8]

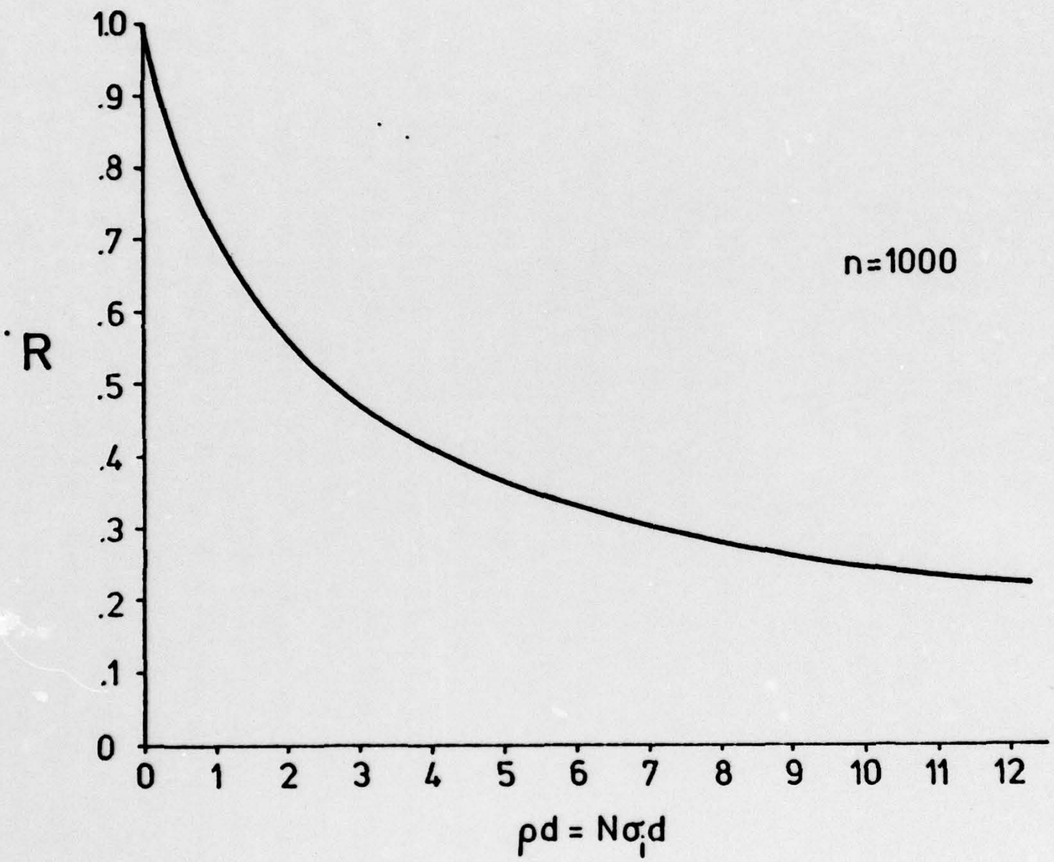

Fig. 2. Results of Simplified Theoretical Model for Fractional Power Density Delivered to Negative Glow as a Function of Gas Pressure and Length of Cathode Fall.

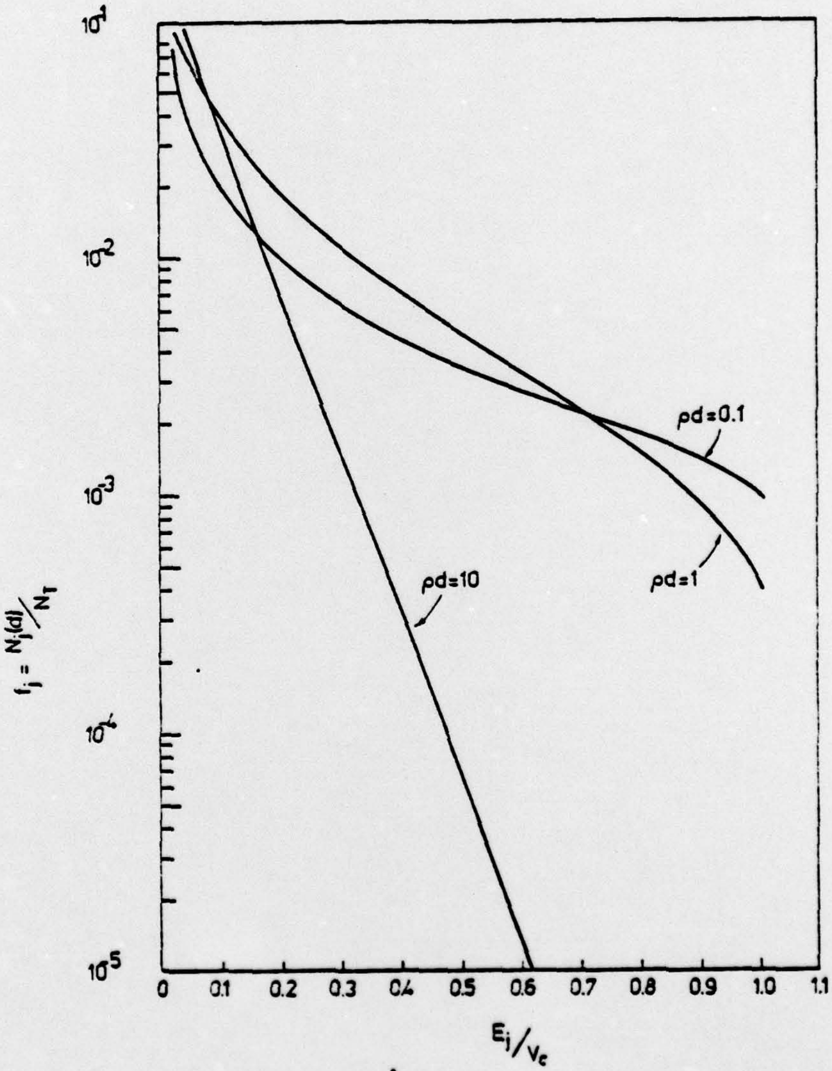

Fig. 3. Electron Energy Distribution from Simplified Theoretical Model.

III. EXPERIMENTAL SETUP

The calorimetric probe employed is shown in Fig. 4. Relative power flux measurements are made using the probe thermistor sealed with epoxy into the end of the pyrex tube. The tube, in turn, was moved longitudinally along the discharge and positioned either on or off the central axis of the discharge. In the presence of a discharge, some heat is deposited in the pyrex tube and can introduce undesirable thermal input to the probe thermistor. To circumvent this problem, water is circulated throughout the areas of the probe within the pyrex tube behind the probe. The temperature of the water bath affects somewhat the dissipation constant of the probe, and a second one is mounted immediately behind the probe thermistor to monitor the temperature of the water bath.

Calibration of this probe was accomplished by first measuring response to an electron flux having a known energy in a high vacuum, and then by measuring changes in the dissipation constant of the probe with variations in water bath temperature and background gas pressure. For the latter measurements a given d.c. bias was applied to the thermistor and the resulting change in resistance for a given power input was measured. Power measurements were made by removing bias to the thermistor to restore initial (without an external input) conditions, and measuring the change in bias power to the probe.

The experiments were carried out on the setup shown in Fig. 5. Helium was used as the working medium and the probe was positioned at various points in relation to a heavy movable aluminum cathode (8.2 cm dia. 2 cm thick). The size of the cathode insured that this structure would not itself become warm enough to radiate additional thermal power to the nearby probe during short periods (5-10 seconds) during which the measurements were made.

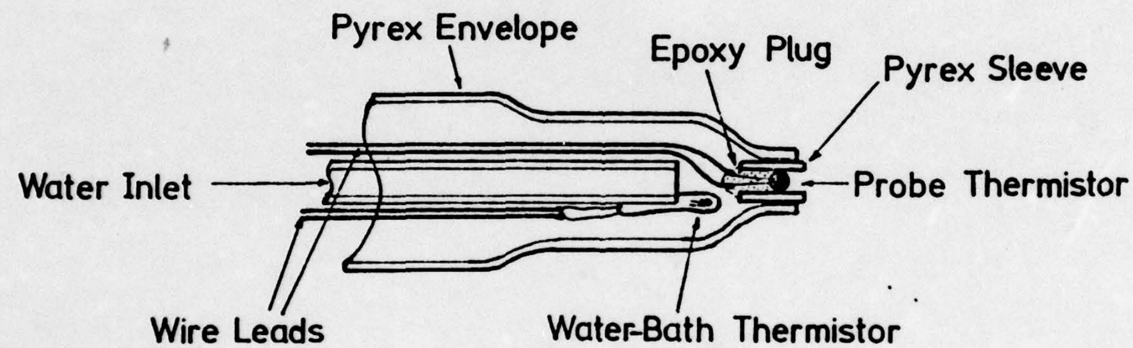

Fig. 4. Probe Design.

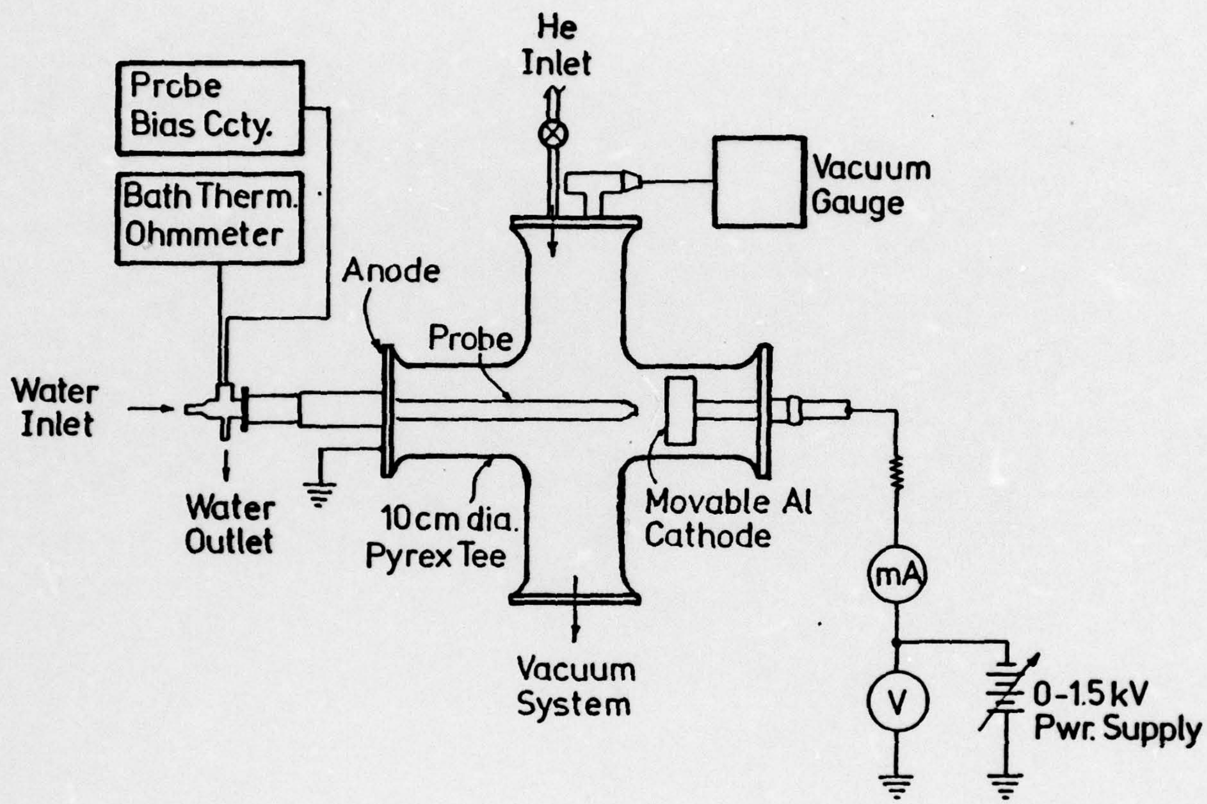

Fig. 5. Experimental Setup.

IV. EXPERIMENTAL RESULTS

Data typical of the longitudinal variation in power detected in the region of the cathode fall-negative glow junction are shown in Fig. 6. The bright onset of the negative glow corresponds roughly to that portion of the curve just beyond the peak, on the side farthest from the cathode. The data in Fig. 6 also show how these regions vary with pressure. As expected, lower neutral density allows greater electron penetration while higher pressure is accompanied by a sharper onset of the negative glow.

In an attempt to determine the sensitivity of this apparatus to sources of power other than beam electrons, measurements were made with a different probe - both with and without a small glass vane (2 cm dia) positioned to block the probe aperture at one point in the dischage. Relative measurements were then made by moving the vane through the axis of the probe to block the beam electrons. While obstructing the probe eliminates the energy deposition by beam electrons, this experiment is, at best, only a qualitative one. The vane itself may absorb and re-radiate heat to the probe, and excited species and surface recombination of electron-ion pairs diffusing in from the unobstructed portion of the discharge can still deposit energy onto the probe. However, with some reservations, the data shown in Fig. 7 using this technique demonstrates considerable sensitivity to the presence of energetic electrons. The unobstructed power is diminished approximately 70% by the presence of the vane approximately two millimeters in front of the probe. This fraction may be further modified, either by the added input of a warm vane or decreased input due to decreased local excitation and ionization.

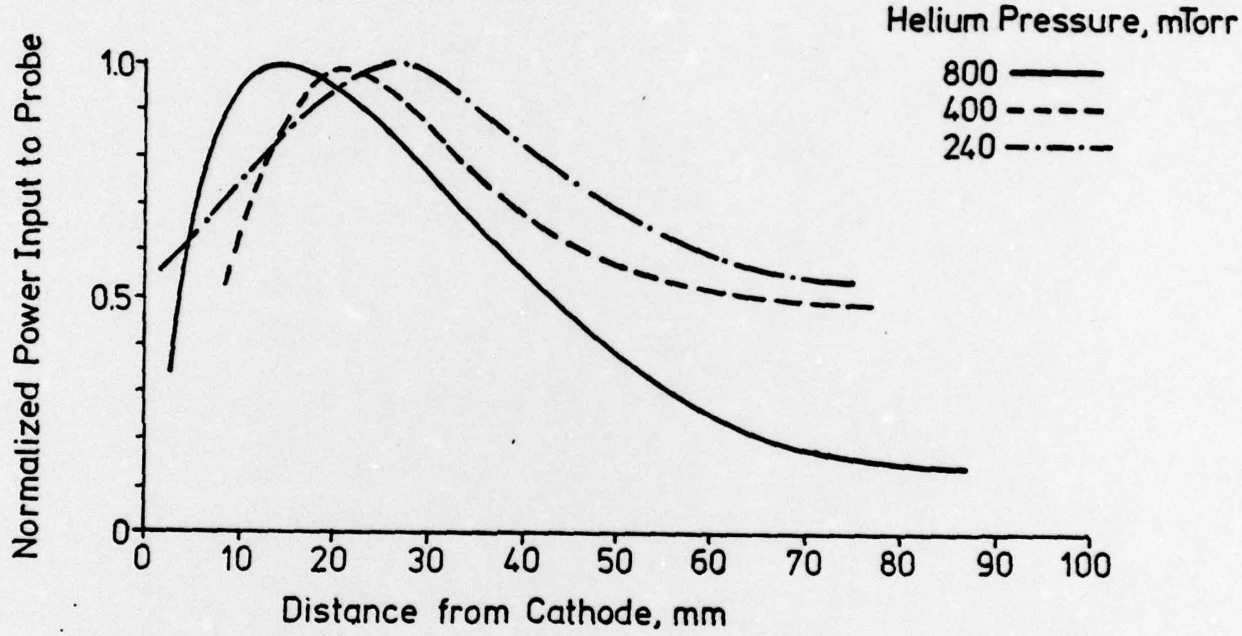

Fig. 6. Normalized Power Input to Probe in Cathode Fall and Negative Glow Regions as a Function of Distance and Gas Pressure.

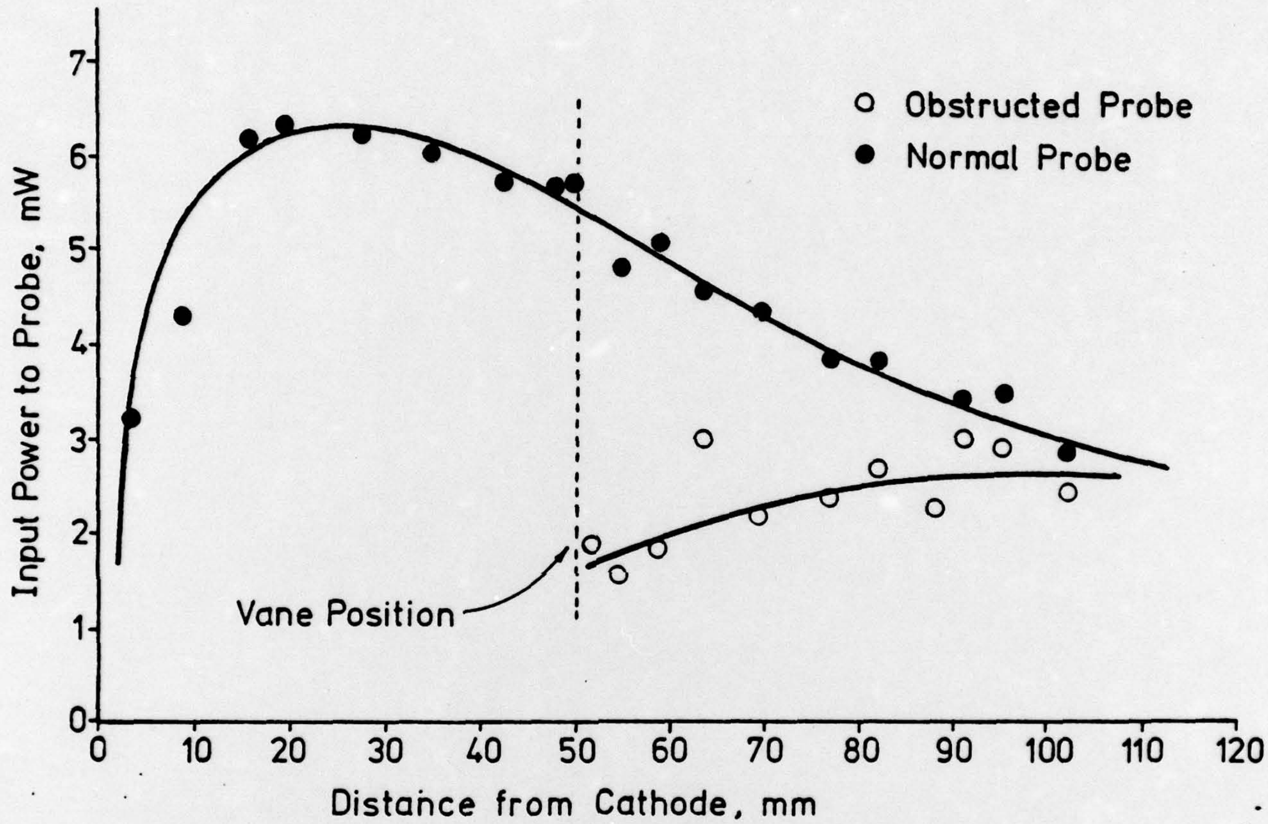

Fig. 7. Results of Measurements to Verify Probe Sensitivity to Beam Electrons.

Figure 8 illustrates the dependence of the ratio R, which is the ratio of power density entering the negative glow to input power flux, on the input power density, P_d, and neutral gas pressure. The rise in R at low input power densities is not yet well understood. Nonetheless, it is clear from these data that R increases somewhat with decreasing neutral density and appears to seek an asymptotic value in the range of 0.3 to 0.4.

Measurements made near the edge of the cathode have shown that, with the present setup, the ratio R is relatively constant (to within 25%) across the edge of the negative glow, dropping significantly only near the edge of the cathode.

V. CONCLUSION

To summarize, the data presented here was obtained by calorimetrically probing the cathode fall-negative glow boundary region of a planar helium discharge in an effort to measure relative power input to the negative glow. Such measurements cannot directly determine the energy spectrum of the electrons and such measurements are sensitive to thermal input due to sources other than beam electrons. Nevertheless, by eliminating major external thermal inputs to the probe and careful calibration of the probe reasonable data have been obtained. In addition, these data show reasonable agreement with a simplified analytical model of the cathode fall region which has been used to predict R ratio values. The implications of these measurements is that no hollow cathode laser can achieve practical efficiency of greater than 30 to 40%.

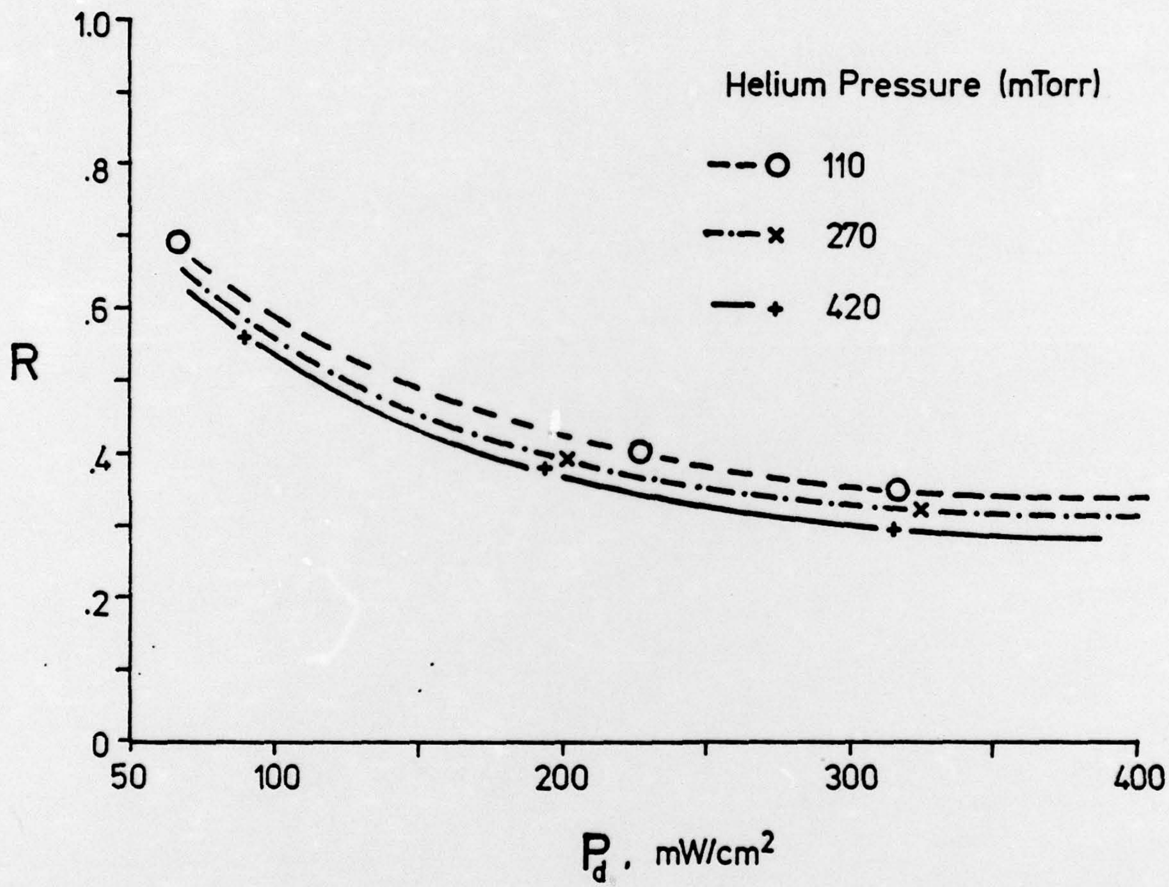

Fig. 8. R, the Ratio of the Power Density Reaching the Negative Glow to Input Power Density, as a Function of Input Power Density, P_d.

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